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USE OF THE DECISION SUPPORT PROBLEM TECHNIQUE FOR PROPULSION ENGINE SELECTION EMPHASIZING RELIABILITY, MAINTENANCE, AND REPAIR FACTORS: A LIMITED EXAMPLE.

Kevin Lynaugh
Naval Surface Warfare Center
Carderock Division, Bethesda, MD

Eric Pogue and Bruce Friedman
ERP Enterprises
506 Sylview Drive
Pasadena, MD 21122

Abstract: A Decision Support Problem Technique (DSPT) is used for the selection of a slow speed diesel engine for the propulsion of a proposed commercial cargo vessel satisfying strategic sealift requirements, and emphasizing reliability, maintenance, and repair factors. A two step procedure is utilized. In the first step, the initial set of five engines and engine variants is reduced to three candidate engines on the basis of generalized criteria. In the second step, engine attribute weights are found through the application of quality function deployment (QFD). Combining the attribute weights with engine attribute ratings generates merit function values for each engine. The analysis is performed with three of the seven attributes related to a reliability, maintenance, and repair criterion: component consumption rate, replacement part cost, maintenance cost(overhaul). The engine chosen is the MAN B&W 5 cylinder K90MC MK VI diesel.

Key Words: customer criteria; decision support problem technique; designer attributes; slow speed diesel engines.

Introduction: The design of sealift ships has been an on-going preoccupation of the U.S. Navy. In support of these efforts, the Maritime Administration (MARAD) of the United States Department of Transportation accomplished the preliminary design of a ship referred to as PD-337. The objective of this study was to develop a commercially viable ship design which would also satisfy the mid-term strategic sealift requirements of the U.S. Navy, via incorporation of "National Defense Features" paid for by the U.S. Government.(1)

The Navy is currently pursuing a broad-based Sealift Ship Technology Development Program and the Naval Surface Warfare Center, Carderock Division (NSWCCD) has a major role in this effort. One component of this program is the Engine Room Arrangement Modeling (ERAM) Project. The purpose of ERAM is to determine a suitable propulsion engine and associated machinery and to integrate these components into an effective and efficient engine room. In support of the MARAD effort a Sealift Research and Development Program was established at the Naval Surface Warfare Center Carderock Division (NSWCCD). One component of this program is engine room arrangement modeling (ERAM). The purpose of ERAM is to determine a suitable

propulsion engine and associated machinery and to integrate these components into an effective and efficient engine room.

Objective: The objective of this study is to examine a limited special case of ERAM, namely, that of selecting for a PD-337 sealift ship a single propulsion engine from an initial set of slow speed two-stroke diesel engines. Emphasis will be placed upon ascertaining the impact of the variation of the reliability, maintenance, and repair factors upon the selection process and its results. (The continuous service rating (CSR) of the engine for the PD-337 concept 24,948 BHP (brake horsepower, metric) with the propeller rating at 89 rpm, with the maximum continuous rating (MCR) being 28,700BHP.)(1-3)

The MAN B&W engines comprising the initial set are the 5K90MC MK VI, with high efficiency turbochargers, the 7L80MC with conventional turbochargers, the 7L80MC with high efficiency turbochargers and turbo compound system (TCS), the 8S70MC with conventional turbochargers, and the 8S70MC with high efficiency turbochargers and TCS.(4-8) The first number in the designation for each engine describes the number of cylinders in that engine and the first letter represents the stroke/bore ratio. (k, short; L, long; S, super long) (4-7)

Approach: The approach to be used to make the preliminary selection is based upon the work of Mistree and others. This work has generated the Decision Support Problem Technique (DSPT). The selection process is derived from the DSPT as a special case. The problem of selection is divided in two phases, the Preliminary Selection Decision Support Problem (PSDSP) and the Final Selection Decision Support Problem (FSDSP).(2,3,8,9)

Discussion and Results: The solution of the PSDSP commences with a description of the concepts. This is the first step. In this case the concepts are the MAN B&W diesel engines. All of the engines are described in literature available from this manufacturer.(4-7)

The second step for solving the PSDSP involves the determination and description of generalized criteria and their respective sets of specific criteria. Four generalized criteria (categories) have been ascertained for this problem:(1) engine operating characteristics, (2) installation, (3) reliability, maintenance, and repair, (4) impact of operations. The specific criteria associated with category (1) are specific fuel oil consumption (SFOC), power match, engine/propeller speed match, and lubrication oil consumption. For category (2) the specific criteria are engine and installation price and ease of installation (size and dimensions). The category (3) specific criteria are the component wear rate, part replacement logistics, time between component failures, spare part cost, and overhaul cost. The category (4) specific criteria are exhaust gas amount, NO_x concentration, vibrations, and noise.(2,3,8)

The SFOC is measured in g/BHP (grams/brake horsepower). By power match is meant the difference between the power generated by the engine at the MCR power level and at its L_1 point. The L_1 point is a point on the engine layout diagram. This diagram shows the layout area within which a combination of engine power and speed can be selected that is optimum for the ship and the expected operating profile. The L_1 point denotes the nominal maximum continuous rating (NMCR) of the engine. Engine/propeller speed match refers to the difference between the rate at

which the propeller rotates at the CSR level (89 rpm) and the rotational rate produced by the engine at NMCR. Lubrication oil consumption refers to the sum of the system oil and cylinder oil consumptions. System oil is measured as kg/cylinder-24 h and cylinder oil is measured as g/BHPh. Engine and installation price will vary with the engine. The ease of installation is a function of the engine weight, volume, and dimensions.(4)

The manufacturer tabulates the average expected consumption of wearing parts over a ten year service period at one service year intervals for a given new engine with a service year assumed to be 6000 hours in duration. Part replacement logistics involves the time to acquire such parts if they are not included in the inventory of the ship operator. Literature from the engine manufacturer gives some information allowing the time factors to be deduced on a relative basis. A similar deduction can be made for time between component failures. Spare part and overhaul cost information are given by the manufacturer in absolute terms.(4-7)

The amount of exhaust gas generated by the various engines and engine variants is presented by the manufacturer for L_1 point operation. Estimates for exhaust gas amount are then calculated for operation at the CSR power level.(4-7) It is assumed that the NO_x concentration would be proportional to the amount of exhaust gas.

The major vibrations of concern are those arising from first and second order moments and the torsional vibrations. It is assumed that the exhaust noise is proportional to the exhaust flow rate and that the structural noise is proportional to the engine vibrational energy. (4-7)

At the outset, it is assumed that all of the generalized criteria are equally important with each other and all of the specific criteria are equally important with each other.

In the third step of the solution of the PSDSP, a datum is chosen with which all of the concepts are to be compared. The concepts comprise the set of MAN B&W engines and engine variations under consideration. It does not matter which engine is selected first, since, in turn, the PSDSP solution will be attained using each engine as the datum.(2,3,8)

For the fourth step, the different engines are compared. The mix of qualitative and quantitative information required is illustrated by the comparisons undertaken utilizing the specific criteria which are found in the domain of the generalized criterion of reliability, maintenance, and repair.(2,3,4,8)

The component wear rate criterion among the five candidate engines has the lowest wear rate assigned to the 5K90MC MK VI. The 7L80MC engines with and without the TCS are taken to be about equal in wear rate and assigned to be between the 5K90MC MK VI and the two 8S70MC engines. The 8S70MC engines are assigned the highest wear rate. The wear rate is taken to be proportional to the number of cylinders within a given engine. The absence or presence of a TCS is assumed to make a negligible difference.(4-7)

The part replacement logistics criterion has equal values assigned to the three engines not having the TCS. The two engines with the TCS also have equal values but these values are lower than

the value assigned to the non-TCS engines. The TCS involves more exhaust piping and a fifteen ton gas turbine and shroud at the base of the engine, thereby covering the side and end of the engine, making work on the scavenger unit and high efficiency turbochargers and related components more difficult.

The time between component failures criterion has equal values assigned to all five engines. On a relative basis the equal value assignment was made because all of the engines have similar MAN B&W parts neglecting the absence or presence of the TCS.(4-7)

The spare part cost criterion rating is assigned to each engine on the basis of quantitative information from the MAN B&W MC program engine selection guidebook. The 5K90MC MK VI gets the highest rating while the two 8S70MC variations get the same lowest rating with the two 7L80MC variations having the same middle rating. The situation with respect to the overhaul cost criterion is similar to that of the spare part cost criterion.(4-7)

Table (1) shows t' preliminary selection scores and ranks for the engine comparisons using the 5K90MC MK VI engine as the datum. In Table (1), "-1" denotes "worse than the datum", "0" denotes "same as the datum," and "1" denotes "better than the datum This table of engine comparisons is the product of the fourth step of the solution of the PSDSP. (2,3,8,9)

The normalized score in Table (1) is also referred to as the merit function value (MFV). The scores are normalized using equation (1):

$$R_{ij} = (A_{ij} - A_{ij}^{min}) / (A_{ij}^{max} - A_{ij}^{min}) \qquad (1)$$

where i denotes one of the engines, j denotes a specific criterion, and A_{ij}^{min} and A_{ij}^{max} represent the lowest and highest possible scores, respectively, of the engine rating A_{ij}. In this Table, the generalized criteria are taken to be of equal weight.(2,3,8,9)

Table (1) then incorporates the fifth step for the PSDSP solution which is the obtaining of the MFVs for each generalized criterion.(2,3,8,9)

In Table (1) the overall score for each engine is the sum of its four MFVs. The ranks for the engines are then obtained by comparing the overall scores. It should be noted that the sum of the MFVs does not constitute an overall MFV (OMFV). The OMFV appears within the context of the sixth step of the PSDSP solution.(2,3,8,9) At the botton of Table (1), the sum of the scores of the generalized criteria establishes the ranking of the engines. The three top ranked engines are the 5K90MC MK VI, the 8S70MC, and the 8S70MC with TCS.

The preliminary selection table using the 7L80MC with TCS as a datum yields the same three top ranked engine although the 5K90MC MK VI is in third place. For the 7L80MC with TCS as datum, the results from the corresponding table are similar to those for the 7L80MC datum. For the 8S70MC as datum, the results are similar to those for Table (1). For the 8S70MC with TCS datum, the preliminary selection table has the 5K90MC MK VI and 8S70MC engines tied for first place with the 8S70MC with TCS in second place.(2,3,8,9)

In the sixth step of the PSDSP solution interactions between the generalized criteria are incorporated into the analysis, the OMFVs are calculated, and the overall ranks are determined. Scenarios are defined by weight assignments. Within a given scenario, each generalized criterion is assigned a weight. The sum of the weights is equal to one. By multiplying each generalized criterion by its corresponding weight and summing over the four products for each engine an OMFV is obtained. For a particular datum and a particular scenario, the OMFVs can be compared with each other to yield a ranking of the engines. The reliability, maintenance, and repair generalized criterion has been assigned weights ranging from .1 to .5 to explore the significance of variations of importance of this criterion to the ascertaining of engine OMFVs and rankings.(2,3,8,9)

Table (2) shows the OMFVs for the 14 scenarios using the 5K90MC MK VI engine as the datum.(2,3,8,9) It is seen that the top rated engine under all of the scenarios is the 5K90MC MK VI. Except for scenarios 6,9, and 13, the second place engine is the 8S70MC with TCS. The third place engine is the 8S70MC, except for scenarios 6, 9, and 13. In scenario 6, the 8S70MC and the 8S70MC with TCS are tied for second place. In scenario 9, the 8S70MC is in second place with the 8S70MC with TCS being in third place. In scenario 13, the 8S70MC is in second place with the 7L80MC being in third place. Except for scenario 13, the top three rated engines under the 5K90MC MK VI datum are the 5K90MC MK VI, the 8S70MC with TCS, and the 8S70MC. (2,3,8,9)

Tables similar to Table (2) are constructed using the other engines and variants as datums. Combining the information generated by these tables selects three engines for the completion of the preliminary selection process. These alternative engines to which the final selection process is to be applied are 5K90MC MK VI, 8S70MC and 8S70MC with TCS.

In the first step of the solution of the FSDSP the alternatives are described. The second step in the solution of the FSDSP requires that the attributes be described and that their relative importances with respect to each other be specified Within the context of this particular problem the **criteria** are taken to be primarily defined by the customer such as the ship operator. The **attributes** are taken to be primarily defined by the designer. The designer attributes are generated by the designer in order to ascertain the significant engineering parameters and characteristics that are involved in satisfying the customer criteria.(4-8)

Table (3a) presents the customer criteria. The two basic types of criteria are the generalized criteria and the specific criteria. The four main headings in Table (3a) constitute the generalized criteria with the specific criteria being listed under these headings. Table (3b) presents the designer attributes listed under the same four headings as in Table (3a). Some of the attributes are the same as the corresponding customer specific criteria. To refine the set of customer criteria into a more manageable set of designer attributes, recourse is made of Quality Function Deployment (QFD) as a translating device. In Tables (3a) and (3b), the three and four character letter and number combinations at the end of a line denote the abbreviations for the factor on that line.(8)

Table (4) is a QFD matrix. The numbers in the first column before the column of customer criteria abbreviations are the relative importances of those criteria on a scale of 0 (no importance) to 5 (extremely important). The boxes starting after the second column contain values that indicate the strength of the relationship between a given criterion and a given attribute listed in the top row. In these boxes, no relationship is denoted by 0, a weak relationship is denoted by 1, a medium strength relationship is denoted by 3, and a strong relationship is denoted by 9. Table (4) is labeled as being scenario #1. The relative importance values in the first column define a scenario. Twenty seven other scenarios were evaluated but are not presented herein due to space limitations. The numbers in the bottom row of Table 4 are importance ratings. These ratings are the sums of products. A product is obtained by multiplying the relative importance rating of a particular criterion by its relationship strength with a given attribute. The sum is obtained by adding up all of the products generated by the same given attribute.(8)

Upon examining all of the twenty eight scenarios, it was found that the same seven attributes are the most important in going from one scenario to another. These seven attributes are :(1)SFOC, (2) oil consumption (including system oil and cylinder oil), (3) rate of component consumption, (4) replacement (spare) part cost, (5) maintenance cost (overhaul), (6) exhaust gas amounts, (7) NO_x amounts within the exhaust.

Referring to Table (3a), the four customer generalized criteria are: (1) engine operating characteristics, (2) installation, (3) reliability, maintenance, and repair, (4) impact of operation on crew, ship, and the environment. Attributes (1) and (2) are classed under criterion (1). Attributes (3), (4), and (5) are classed under criterion(3). Attributes (6) and (7) are classed under criterion (4). Of particular interest for this investigation are the three reliability, maintenance and repair attributes(3), (4), and (5). The seven attributes having the highest importance ratings are those chosen for utilization in the final engine selection process.

Table (5) presents the normalized relative importance ratings (NRIRs) for the seven most important attributes for each scenario. An NRIR is obtained by dividing the importance rating of the particula attribute by the sum of the importance ratings of all seven attributes for a given scenario. The NRIRs of Table (5) represent the completion of the second step of the solution of the FSDSP. The method by which the NRIRs are determined is a variation of the ranking method for the determination of the weights for the relative importance of the attributes. The weights are taken to be identical to the NRIRs. In the ranking method, the attribute ranks and weights are proportional to their respective importances with the weights being normalized prior to their utilization in the analysis.(8)

For the component consumption rate attribute NRIR over all of the scenarios, the values vary from 0.119 to 0.160. For the replacement part cost attribute, the NRIR range is from 0.103 to 0.132. For the maintenance cost (overhaul) attribute, the NRIR range is from 0.417 to 0.211.

For a given scenario, the smallest range in NRIRs among the three attributes associated with the reliability, maintenance, and repair criterion is found in scenario #3 (.035) while the largest range is found in scenario #27 (.078). Referring to Table (3a) for the customer criteria, it is found that the specific criteria C3a, C3b, C3c, C3d, and C3e comprise the reliability, maintenance, and repair

generalized criterion. In scenario #3, the QFD relative importance values for these specific criteria are 3,2,1,5, and 4, respectively. In scenario #27, the QFD relative importance values for these specific criteria are 5,5,5,5, and 5, respectively. These two sets of values are indicative of the possibility that increasing the value of the customer criteria is related to an increase in the NRIR value range for the relevant designer attributes.

In the third step of the solution of the FSDSP, the scales of the attributes are specified and the alternative engines are rated with respect to each attribute. The interval scale was selected for all of the seven attributes.(8)

Tables (6a)-(6g) present the criteria for interval scale creation for the seven attributes. Attributes (1), (2), (4), (5), and (6) are associated with more quantitative information while attributes (3) and (7) are associated with more qualitative information. Two of the attributes related to the reliability, maintenance, and repair generalized criterion have associated more quantitative information while one related attribute has associated more qualitative information

The upper and lower limits for each of the attribute criterion scales is determined by the limits of the three alternative engines with respect to each of the attributes. As part of the third step, each alternative engine is rated with respect to each attribute.

In the fourth step of the solution of the FSDSP, the ratings are normalized. The normalization for any set of attribute values is performed by dividing the given attribute value by the maximum attribute value. Under the component consumption rate attribute all three engines have a normalized rating of 1. Under both the replacement part cost and maintenance cost attributes, the 5K90MC MK VI has a rating of 1 with the 8S70MC and the 8S70MC with TCS both having ratings of 0.1

In the fifth step, the merit function is calculated for each alternative engine. A linear model is employed. A term is formed for each attribute comprising the product of the NRIR of that attribute and the normalized rating of the engine for that attribute. The sum of these products over all seven attributes is calculated to get the merit function value for the engine. Table (9) presents the merit function values of the three alternative engines under the 28 scenarios considered. For all of the scenarios the merit function values in descending order are those for the 5K90MC MK VI, the 8S70MC with TCS, and the 8S70MC with conventional turbochargers.

Conclusion: It is concluded that the top ranked engine is the 5K90MC MK VI, the second ranked engine is the 8S70MC with TCS, and the third ranked engine is the 8S70MC with the conventional turbochargers. Considering the broad range of scenarios encountered, the engine to be selected for the propulsion of the sealift cargo vessels is the 5K90MC MK VI.

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Table 1

Preliminary Selection: scores and ranks

General Criteria	Specific Criteria	Concepts: DATUM 5 K-90MC	7 L-80 MC	7 L-80 MC (TCS)	8 S-70 MC	8 S-70 MC (TCS)
ENGINE OPERATING CHARACTERISTICS						
	SPECIFIC FUEL OIL CONSUMPTION	0	-1	1	-1	1
	POWER MATCH	0	-1	-1	1	1
	ENGINE/PROPELLER SPEED MATCH	0	1	1	1	1
	LUBE OIL CONSUMPTION	0	-1	-1	-1	-1
	Score	**0**	**-0.5**	**0**	**0**	**0.5**
	Normal Score	**0.5**	**0**	**0.5**	**0.5**	**1**
INSTALLATION						
	ENGINE AND INSTALLATION PRICE	0	0	0	0	0
	EASE OF INSTALLATION (SIZE)	0	1	1	1	1
	Score	**0**	**0.5**	**0.5**	**0.5**	**0.5**
	Normal Score	**0**	**1**	**1**	**1**	**1**
RELIABILITY MAINTENANCE AND REPAIR						
	COMPARATIVE WEAR RATE	0	-1	-1	-1	-1
	PART REPLACEMENT LOGISTICS	0	0	-1	0	-1
	TIME BETWEEN COMPONENT FAILURES	0	0	0	0	0
	SPARE PART COST	0	-1	-1	-1	-1
	OVERHAUL COST	0	-1	-1	-1	-1
	Score	**0**	**-0.6**	**-0.8**	**-0.6**	**-0.8**
	Normal Score	**1**	**0.25**	**0**	**0.25**	**0**
IMPACT OF OPERATIONS						
	EXHAUST GAS AMOUNT	0	-1	-1	-1	-1
	NOx CONCENTRATION	0	-1	-1	-1	-1
	VIBRATIONS	0	1	1	1	1
	NOISE	0	0	0	0	0
	Score	**0**	**-0.25**	**-0.25**	**-0.25**	**-0.25**
	Normal Score	**1**	**0**	**0**	**0**	**0**
OVERALL SCORES AND RANKS						
	Sum of Scores	**2.5**	**1.25**	**1.5**	**1.75**	**2**
	Ranks	**1**	**5**	**4**	**3**	**2**

Table 2

Overall Merit Function Values

K-90 DATUM

Acronym	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7
5 K-90 MC	**0.75**	**0.7**	**0.7**	**0.75**	**0.75**	**0.8**	**0.8**
7 L-80 MC	0.2	0.175	0.15	0.15	0.175	0.2	0.175
7 L-80 MC with TCS	0.25	0.3	0.3	0.25	0.25	0.2	0.2
8 S-70 MC	**0.35**	**0.375**	**0.35**	**0.3**	**0.325**	**0.3**	**0.275**
8 S-70 MC with TCS	**0.4**	**0.5**	**0.5**	**0.4**	**0.4**	**0.3**	**0.3**

Acronym	Scenario 8	Scenario 9	Scenario 10	Scenario 11	Scenario 12	Scenario 13	Scenario 14
5 K-90 MC	**0.625**	**0.8**	**0.7**	**0.6**	**0.65**	**0.85**	**0.75**
7 L-80 MC	0.3125	0.225	0.125	0.375	0.25	**0.225**	0.225
7 L-80 MC with TCS	0.375	0.2	0.3	0.4	0.35	0.15	0.25
8 S-70 MC	**0.4375**	**0.325**	**0.325**	**0.475**	**0.4**	**0.275**	**0.375**
8 S-70 MC with TCS	**0.5**	**0.3**	**0.5**	**0.5**	**0.5**	0.2	**0.4**

Table 3a ***Customer Criteria:***

1. ENGINE OPERATING CHARACTERISTICS
   - a. SFOC (CSR, L_1) **C1a**
   - b. power match (CSR, L_1) **C1b**
   - c. engine/propeller match (CSR, L_1) **C1c**
   - d. lubricating oil consumption **C1d**
2. INSTALLATION
   - a. cost of engine itself and cost of installation **C2a**
   - b. ease of installation, (volume and weight) **C2b**
3. RELIABILITY, MAINTENANCE AND REPAIR
   - a. component wear rate **C3a**
   - b. part replacement logistics **C3b**
   - c. mean time between and mean duration of overhauls **C3c**
   - d. spare part cost **C3d**
   - e. maintenance cost (overhaul) **C3e**
4. IMPACT OF OPERATION ON CREW, SHIP AND THE ENVIRONMENT
   - a. exhaust gas amount **C4a**
   - b. No_x concentration in exhaust **C4b**
   - c. vibration **C4c**
   - d. noise **C4d**

Table 3b ***Designer Attributes:***

1. ENGINE OPERATING CHARACTERISTICS
   - a. SFOC, CSR, g/BHPh **A1a**
   - b. power match (CSR/L_1) **A1b**
   - c. engine propeller speed match (CSR/L_1) rpm **A1c**
   - d. 1 system oil consumption Kg/day **A1d1**
     2 cylinder oil consumption CSR/BHPh **A1d2**
2. INSTALLATION
   - a. 1. engine cost, $ **A2a1**
     2. installation cost, $ **A2a2**
   - b. 1. engine mass in tons **A2b1**
     2. H3 (electrical jib crane)+A, mm **A2b2**
     3. L1 (minimum length), mm **A2b3**
3. RELIABILITY, MAINTENANCE AND REPAIR
   - a. number of components consumed in given time period, number of parts divided by number of hours **A3a**
   - b. 1. average length of time to obtain parts, hours **A3b1**
     2. longest time to obtain a part, hours **A3b2**
   - c. 1. mean time between breakdowns, hours **A3c1**
     2. mean duration of breakdowns, hours **A3c2**
   - d. spare part cost, $ **A3d**
   - e. maintenance cost (overhaul), labor $/(nominal Bhp x 6000hrs.) **A3e**
4. IMPACT OF ENGINE OPERATION ON CREW, SHIP, AND ENVIRONMENT
   - a. exhaust gas amount at CSR **A4a**
   - b. No_x concentration, kg/hr **A4b**
   - c. 1. external unbalanced moments, PRU,Nm/KW, (CSR) **A4c1**
     2. guide force moments, CSR, KNM **A4c2**
     3. axial vibrations, CSR, sec^{-1} **A4c3**
     4. torsional vibrations, CSR, sec **A4c4**
   - d. 1. exhaust gas noise, CSR, dB **A4d1**
     2. airborne noise, CSR, dB **A4d2**
     3. structure-borne noise excitation, CSR, dB, **A4d3**

table 4

QFD Matrix

scenario #1

rel. importance	user\designer	A1a	A1b	A1c	A1d1	A1d2	A2a1	A2a2	A2b1	A2b2	A2b3	A3a	A3b1	A3b2
2	C1a	9	3	3	3	3	3	0	1	1	1	1	0	0
2	C1b	3	9	3	3	3	3	0	1	1	1	1	0	0
2	C1c	3	3	9	3	3	3	0	1	1	1	1	0	0
2	C1d	3	3	3	9	9	3	0	1	1	1	3	0	0
5	C2a	1	1	1	1	1	9	9	3	3	3	1	0	0
5	C2b	1	1	1	1	1	3	3	3	9	9	1	0	0
4	C3a	1	3	3	3	3	3	0	1	1	1	9	0	0
4	C3b	0	0	0	0	0	1	0	0	0	0	0	9	9
4	C3c	1	1	1	3	3	3	0	1	1	1	3	0	0
4	C3d	0	0	0	0	0	3	0	3	1	1	9	0	0
4	C3e	1	1	1	3	3	3	0	3	1	1	9	3	3
3	C4a	9	1	1	3	3	3	1	1	1	1	3	1	1
3	C4b	9	1	1	3	3	3	1	1	1	1	3	1	1
3	C4c	3	3	3	3	3	3	1	1	1	1	3	1	1
3	C4d	3	3	3	3	3	3	1	1	1	1	3	1	1
	imp. ratings	130	90	90	118	118	172	72	82	96	96	178	60	60

rel. importance	user\designer	A3c1	A3c2	A3d	A3e	A4a	A4b	A4c1	A4c2	A4c3	A4c4	A4d1	A4d2	A4d3
2	C1a	1	0	0	1	9	9	1	1	1	1	1	1	1
2	C1b	0	0	0	1	3	3	3	3	3	3	1	1	1
2	C1c	0	0	0	1	3	3	3	3	3	3	1	1	1
2	C1d	3	0	9	9	9	9	3	3	3	3	1	1	1
5	C2a	0	0	0	0	1	1	1	1	1	1	1	1	1
5	C2b	0	0	0	0	0	0	1	1	1	1	1	1	1
4	C3a	3	1	9	9	3	3	1	1	1	1	1	1	1
4	C3b	0	9	0	9	1	1	0	0	0	0	0	0	0
4	C3c	9	9	3	9	1	1	3	3	3	3	3	3	3
4	C3d	0	1	9	9	3	3	1	1	1	1	1	1	1
4	C3e	3	9	3	9	1	1	1	1	1	1	1	1	1
3	C4a	1	0	3	3	9	9	0	0	0	0	9	0	0
3	C4b	1	0	3	3	9	9	0	0	0	0	0	0	0
3	C4c	1	0	3	3	3	3	9	9	9	9	0	9	9
3	C4d	1	0	3	3	3	3	9	9	9	9	9	9	9
	imp. ratings	80	116	150	240	161	161	108	108	108	108	96	96	96

Table 5

Normalized Relative Importance Ratings from the QFD scenarios

	scenario #'s									
	1	2	3	4	5	6	7	8	9	10
Specific Fuel Oil Consumption	0.114	0.145	0.13	0.125	0.122	0.142	0.119	0.124	0.131	0.128
Lube/Cylinder Oil Consumption	0.104	0.111	0.099	0.115	0.114	0.114	0.113	0.112	0.111	0.123
Component Consumption Rate	0.156	0.136	0.16	0.12	0.133	0.119	0.152	0.149	0.124	0.125
Replacement Part Cost	0.132	0.103	0.125	0.119	0.124	0.116	0.125	0.121	0.124	0.116
Maintenance Cost (Overhaul)	0.211	0.176	0.18	0.201	0.191	0.165	0.197	0.192	0.184	0.18
Exhaust Gas Amounts	0.141	0.164	0.154	0.16	0.158	0.172	0.147	0.151	0.163	0.164
NOx Amounts within Exhaust	0.141	0.164	0.154	0.16	0.158	0.172	0.147	0.151	0.163	0.164

	scenario #'s									
	11	12	13	14	15	16	17	18	19	20
Specific Fuel Oil Consumption	0.119	0.143	0.128	0.119	0.119	0.119	0.119	0.141	0.141	0.141
Lube/Cylinder Oil Consumption	0.108	0.115	0.111	0.108	0.108	0.108	0.108	0.114	0.114	0.114
Component Consumption Rate	0.137	0.12	0.136	0.138	0.138	0.138	0.138	0.119	0.119	0.119
Replacement Part Cost	0.128	0.115	0.122	0.128	0.128	0.128	0.128	0.116	0.116	0.116
Maintenance Cost (Overhaul)	0.199	0.164	0.188	0.199	0.199	0.199	0.199	0.166	0.166	0.166
Exhaust Gas Amounts	0.154	0.172	0.158	0.154	0.154	0.154	0.154	0.172	0.172	0.172
NOx Amounts within Exhaust	0.154	0.172	0.158	0.154	0.154	0.154	0.154	0.172	0.172	0.172

	scenario #'s							
	21	22	23	24	25	26	27	28
Specific Fuel Oil Consumption	0.121	0.12	0.121	0.126	0.149	0.153	0.115	0.131
Lube/Cylinder Oil Consumption	0.113	0.112	0.112	0.123	0.102	0.117	0.102	0.108
Component Consumption Rate	0.132	0.132	0.132	0.115	0.13	0.113	0.149	0.151
Replacement Part Cost	0.125	0.125	0.125	0.12	0.103	0.108	0.132	0.125
Maintenance Cost (Overhaul)	0.194	0.194	0.194	0.194	0.178	0.147	0.21	0.174
Exhaust Gas Amounts	0.158	0.158	0.158	0.161	0.169	0.178	0.146	0.156
NOx Amounts within Exhaust	0.158	0.158	0.158	0.161	0.169	0.178	0.146	0.156

Table 6 Criteria for interval scale creation

6a

ATTRIBUTE #1	**Specific Fuel Oil Consumption** (g/BHPh)	RATING
Lowest consumption	119	10 to 9
	↓	8 to 7
		6 to 5
		4 to 3
maximum consumption	126	2 to 1

6b

ATTRIBUTE #2	**Lube / Cylinder Oil Consumption** kg of cylinder oil (lube oil consumption equal)	RATING
lowest consumption	70 kg	10 to 9
	↓	8 to 7
		6 to 5
		4 to 3
maximum consumption	72 kg	2 to 1

6c

ATTRIBUTE #3	**Rate of Component Consumption** # of components consumed	RATING
minimum component loss	resultant expenditures insignificant	10 to 9
	↓	8 to 7
		6 to 5
		4 to 3
maximum component loss	significant resultant expenditures	2 to 1

6d

ATTRIBUTE #4	**Replacement Part Cost** cost (per BHP x 6000hrs.)	RATING
minimum part cost	8 DKK	10 to 9
	↓	8 to 7
		6 to 5
		4 to 3
maximum part cost	11 DKK	2 to 1

criteria for interval scale creation cont'd

6e

ATTRIBUTE #5	**Maintenance Cost (Overhaul)**	
	cost (per BHP x 6000hrs.)	RATING
minimum overhaul cost	7.5 DKK	10 to 9
	↓	8 to 7
		6 to 5
		4 to 3
maximum overhaul cost	12 DKK	2 to 1

6f

ATTRIBUTE #6	**Exhaust Gas Flow**	
	flow (kg/hr)	RATING
minimum amount	139,000	10 to 9
	↓	8 to 7
		6 to 5
		4 to 3
maximum amount	144,000	2 to 1

6g

ATTRIBUTE #7	**NOx Concentration within exhaust**	
	concentration	RATING
minimum concentration	minimal threat to environment and no money	10 to 9
	needed for fines/reduction of NOx	8 to 7
	↓	6 to 5
		4 to 3
maximum concentration	concentration is threat to environment a[illegible]	2 to 1

Table 7

Merit Function Values

SCENARIO #'S

ALTERNATIVES	1	2	3	4	5	6	7	8	9	10	11	12	13	14
5 Cylinder K-90 MC	0.931	0.912	0.924	0.925	0.927	0.915	0.929	0.926	0.921	0.923	0.928	0.915	0.924	0.929
8 Cylinder S-70 MC	0.343	0.342	0.357	0.325	0.338	0.336	0.344	0.344	0.33	0.332	0.335	0.334	0.338	0.337
8 Cylinder S-70 MC with TCS	0.437	0.472	0.474	0.437	0.448	0.46	0.451	0.456	0.448	0.447	0.442	0.463	0.453	0.444

SCENARIO #'S

ALTERNATIVES	15	16	17	18	19	20	21	22	23	24	25	26	27	28
5 Cylinder K-90 MC	0.929	0.93	0.928	0.915	0.916	0.914	0.927	0.927	0.927	0.924	0.911	0.902	0.931	0.922
8 Cylinder S-70 MC	0.337	0.338	0.336	0.333	0.316	0.332	0.334	0.334	0.334	0.321	0.315	0.331	0.341	0.35
8 Cylinder S-70 MC with TCS	0.444	0.445	0.443	0.46	0.449	0.459	0.443	0.442	0.443	0.435	0.449	0.469	0.444	0.468